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ABSTRACT

Distillation in the chemistry laboratory is an essential part of a practicing chemists' and a chemistry educators' work. Nevertheless, regardless of the degree of importance in each of the aforementioned professions, few educational studies on teaching and learning distillation exist. In an effort to rectify this oversight, the Department of Chemical Education at Utrecht University engaged first year chemistry majors in a qualitative study aimed at acquiring an understanding of the processes of conceptual development that do, or do not, take place when students are performing distillation experiments. The results include: (1) discussions of distillation from a chemical point of view; (2) detailed descriptions of the problems that occur when students are distilling during laboratory experiments; (3) an interpretations of the problems; and (4) ways to avoid problems with the help of different teaching strategies. (ZWH)

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TEACHING AND LEARNING DISTILLATION IN CHEMISTRY LABORATORY COURSES

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Introduction

Distillation is an important part of many practising chemists' work. Hence, instruction concerning laboratory distillation is considered an essential part of chemistry education at the university level. However, little is known about the learning and teaching processes involved. This is not because distillation is easy: from our own teaching experience we know that students have many difficulties with distillation. We presume that other chemistry teachers share this experience. Nevertheless, to our knowledge, educational studies - as opposed to anecdotes and opinions - on teaching and learning distillation do not exist. This study tries to make up for this omission.

The Department of Chemical Education at Utrecht University has a on-going research program which focuses on the laboratory courses of our Faculty of Chemistry. The program pays attention to what we see as the central themes in the chemistry laboratory: measuring and making. During the first half of the nineteen eighties, our Department was involved in developing new educational material on separation techniques and physical chemical principles for the first year chemistry laboratory course (Mulder & Verdonk, 1984). Partly as a result from this developmental work the interest shifted towards the more fundamental problem of how students learn measuring in the laboratory (Goedhart, 1990; Goedhart & Verdonk, 1991). At present, research focuses on teaching and learning organic synthesis (Van Keulen, 1992). Since distillation is an operation which can occur both in analytical, physical, and synthesis experiments, our attention was repeatedly drawn to it. In this study, we integrate the findings on distillation of the three different research strands into one. We discuss distillation from a chemical point of view; we present detailed descriptions of the problems that occur when students are distilling during laboratory experiments; we interpret the problems; and we show ways to avoid them with the help of different teaching strategies.

The research projects of our Department have a distinct qualitative and interpretive nature (Van Keulen & Verdonk, 1993), aiming at an understanding of the processes of conceptual development that do, or do not, take place when students are performing laboratory experiments. The students described in this study are first year chemistry students (all planning to major in chemistry) following an obligatory two-semester general chemistry laboratory course.

We make use of many of the conventional strategies for qualitative data gathering (Gallagher, 1991; Glaser & Strauss, 1967): observation of the educational processes (taking notes, video taping, asking questions); open interviews with students, teachers and faculty members; document analysis; and, above all, analysis of transcriptions of the discourse between students and between student(s) and teacher.

An important part of our research method is the construction of new, less controlled laboratory experiments. In these experiments, students have more freedom to act, and thus are in need of

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justifications. As a result, discussions take place more often and provide the researcher with more and richer information.

Distillation from a chemical point of view

A chemist, when distilling, should be able to make correct decisions in order to obtain satisfying results. These decisions should be based on an understanding of what is going on in the distillation process. This description gives the clue to what presumably are the learning goals with regard to distillation in the chemical curriculum: 'make correct decisions', 'obtain satisfying results', 'understanding of what is going on'. In this section we analyse what is meant by these terms.

In this analysis we use the following description of distillation:

Distillation is an activity employed to change the composition of a liquid mixture. In order to achieve this goal the mixture is heated and/or the pressure on the mixture is reduced. The vapor which is generated in this process separates from the liquid due to gravity. The vapor is treated in such a way that the difference in composition between the condensed vapor and the residual liquid is maximized. The condensed vapor can be collected in fractions with desired composition on the basis of a thermometer indication.

What does a chemist do when she or he is confronted with a liquid mixture which has to be purified? This depends on the assumed composition of the mixture. If the mixture is inhomogeneous, mechanical separation using a Buchner funnel or a separatory funnel commonly is more convenient than distillation. If the component of interest is a soluted solid, rotation vaporization often is first choice. If the important components are liquids, then the choice of a distillation method depends on what can be assumed with respect to the composition of the mixture (i.e., identity and relative amount of the components). The chemist compares the boiling points of the components and checks for azeotropes in order to estimate whether or not distillation will lead to increased purity in either distillate or residue. When the differences in boiling point between the components to be separated are small, fractional distillation can be applied. To avoid undesired chemical reactions during the (physical) separation a method can be chosen which minimizes decomposition. This can be either steam distillation or vacuum distillation. Steam distillation, however, is never the last stage of a purification process, because the distillate always contains water. Steam distillation is mainly applied when the mixture is complex and the component of interest has a higher volatility than other compounds present. It is also applied in those cases where other means of separation, like extraction, lead to difficulties due to other compounds present.

When the method has been selected the size of the apparatus is determined in relation to the amount of matter. The size of the distilling flask depends on the total quantity of the mixture. The composition of the mixture has to be estimated in order to determine the size and kind of the fractionating column, the capacity of the condenser, and the size and number of the receiving flasks. Obviously, when the quantity of the liquid is small, using a large distilling flask and column leads to a large hold up and a loss of yield.

Other important aspects concern controlling the distillation process itself: the temperature, the heat flow, the fractionating process, the condensing, the temperature measurement. In vacuum distillation, it is also necessary to control pressure, superheating and atmosphere. Decisions have to be made regarding the endpoint of the distillation, the moment of changing receiving flasks, and the question whether or not the distillation has to be repeated.

From a theoretical point of view, one should think that a chemist uses insights and quantitative data from thermodynamics and phase theory. However, our own experience, reinforced by discussions with other chemists in our Faculty, compelled us to admit that this is seldom the case. Most chemists use rules of thumb and rough approximations which are not backed up by strict theory. This led us to reflect on the relations between thermodynamics and distillation. These relations indeed are problematic, mainly because the distillation apparatus as a whole is

not in a state of thermodynamic equilibrium, and we came to realize that distillation is not a topic which can easily be derived from theory. This has consequences for education, of course.

Students' prior knowledge

During secondary education, students will have acquired some knowledge of distillation, although not many will have carried out a distillation themselves. In The Netherlands, we can safely assume that chemistry freshmen are familiar with the following description: "Distillation is the process of vaporizing a substance, condensing the vapor, and collecting the condensate in another container. This technique is useful for separating a mixture when the components have different boiling points. It is the principal method for purifying a liquid"(Pavia, Lampman, & Kriz, 1982). However, our experience with laboratory courses made us cautious about the depth of students' understanding of such a statement. Our own work (Goedhart & Verdonk, 1991) and the few studies reported in literature in this area show that the properties of pure substances and mixtures are not always understood properly, and that the concepts of boiling, evaporation, and vapor pressure are problematic (Osborne & Cosgrove, 1983; Russell, Harlen, & Watt, 1989).

Description of the problems

At Utrecht University, distillations usually are carried out in more or less controlled experiments - that is, with detailed experimental procedures and known chemical outcomes (Boud, Dunn, & Hegarty-Hazel, 1986). Most distillations occur during organic synthesis experiments, but there is also a distillation in an experiment on measuring thermodynamic parameters. Distillation techniques are discussed in detail in a lecture course on analytical chemistry. Principles of distillation are treated in a lecture course on phase theory. We assume that similar situations exist at other universities. Of course, educational systems in various countries and, in the same country, at different institutions, may show huge differences in quantity and complexity both of the experimental work and of the theoretical explanations, but the structure seems to be more or less universal.

Over the years, we have observed many problems of students who are performing distillations which, in our opinion, do not fall into the categories of blunders or simple mistakes. In this section, we just describe them. In the next section, we will try to categorize them .

Choice of a distillation technique

In many laboratory experiments, the specific distillation technique is prescribed in some detail. When this is not the case, most students as a matter of fact choose normal distillation, even when there are very good reasons to choose fractionating distillation or vacuum distillation. Sometimes vacuum distillation is chosen because it is thought that this technique leads to higher purity. One of the authors remembers, as a student, to have carried out steam distillations using a fractionating column. Neither the teaching assistants nor the professor in charge ever made a remark.

Size of the apparatus

Students do not pay much attention to the size of the apparatus. They assemble the apparatus from pieces of glass ware they happen to have at hand. They seem to use aesthetic criteria rather than rules of thumb to establish the size of the distilling flask. The remainder of the glass ware is chosen to fit at the joints. Often, a distillation is repeated using the same distilling apparatus, even when the quantity of liquid had decreased considerably. Many students automatically choose receiving flasks the same size as the distilling flask.

Cooling capacity of the condenser

The cooling capacity of the condenser and the temperature of the receiving flask are seldom related to the properties of the fractions to be condensed. For example, students are surprised that diethyl ether does not condense during a vacuum distillation. When applying steam distillation, students often do not consider melting points, although some components may crystallize in the condenser.

The top thermometer

Students, when distilling for the first time, do not seem to understand the place of the thermometer. When a two-neck distilling flask is used, many students place the thermometer on the second neck. When assembling a vacuum distillation apparatus, many students position the thermometer at the place of the capillary and not on top of the distilling head. When they start heating, almost all students expect that the top thermometer should read the temperature of the liquid. The fact that the thermometer initially remains at room temperature comes as a surprise.

The independent-substance conception

Most students expect that the components of the liquid mixture will vaporize one after another, in the order of the respective boiling points. They expect that the boiling liquid will have the boiling point temperature of the component which is thought to vaporize at that moment. This is perhaps the reason why they want to put the thermometer in the boiling liquid, and not on the distilling head. We propose to call this the independent-substance conception. This conception is inadvertently strengthened by many distillation experiences. After all, when the separation is complete, the thermometer does indicate the boiling points of pure components. Students have problems when the thermometer indication does not correspond with the boiling point of a pure substance, for example when separation is incomplete. Such deviations from the ideal make it difficult to use the temperature as an indicator for composition and consequently for ending the distillation or changing receiving flasks.

Many students expect that purification through distillation is possible whenever there is a difference in boiling point between the components, however small this difference may be. We have seen students trying to distil ethyl acetate (b.p. 77.1°C) out of a crude reaction mixture also containing water, ethanol (b.p. 78.5°C) and acetic acid. They seriously expect the distillate to be pure ethyl acetate. Both the actual top temperature (70°C, due to the ethanol-ethyl acetate-water azeotrope) and the impure result come as a surprise.

Recognizing and interpreting azeotropes

Especially azeotropic distillations showed us the dominant influence of the independent-substance conception. For instance, when distilling a dilute aqueous solution of hydrochloric acid, students are reluctant to believe that the distillate will be pure water. They certainly refuse to drink it. And, preparing absolute ethanol from a solution containing less than 4% of water, students expect that the distillate will be the purified ethanol, whereas it is the residue.

Students are always confused when, during distillation, the thermometer indicates a temperature below the boiling points of all the components which are present. This is the case when the mixture forms a low boiling azeotrope, but students are also baffled by the boiling point of a steam distillation. Some water-containing crude synthesis mixtures unexpectedly behave like a steam distillation, and this gives rise to even greater confusion.

The relation between vapor and vapor pressure

When performing a simple distillation at normal pressure, students sometimes unintentionally assemble an apparatus which is closed. More precisely, it does not seem to matter to them whether or not the apparatus is closed. This sometimes leads to dangerous situations because the apparatus cannot accommodate increased pressure. When applying vacuum distillation, some students start heating before reducing the pressure. In such cases, especially low boiling liquids (such as diethyl ether) cause problems because the high vapor pressure leads to immediate flooding in the apparatus when the pressure finally is reduced. These observations seem to indicate that concepts such as pressure and vapor pressure are obscure. A related problem is that pressure measurement often takes place not in the distillation apparatus itself but at the pump, for example when a water aspirator with a mercury manometer is used. Many students do not check the position of the valve between the pump and the apparatus. Sometimes, when the valve happens to be in a wrong position, this gives rise to unexpected pressure building in the apparatus. With the valve in another position, pressure may only be reduced in the aspirator, whereas the distillation apparatus remains open to the air. In such cases

many students just carry on, even when the expected lowered boiling point is exceeded considerably.

Control of heating

The amount of heat employed is seldom controlled. Only very few students control the takeoff (the rate at which the distillate leaves the condenser) using some rule of thumb such as one drop every two seconds. Flooding in the head or in the column is hardly ever recognized as a threat to the quality of the separation process. This indicates that students do not understand that cycles of vaporizing and condensing have to be materialized in space and time for separation to take place.

Using the Clausius-Clapeyron equation

Students with some previous training in thermodynamics are able to use the Clausius-Clapeyron equation to calculate a boiling point under reduced pressure, or to calculate the enthalpy of vaporization from boiling point measurements at different pressures. However, they are unaware of the fact that, from the point of view of thermodynamics, these are not exact calculations. The practical value is limited to pure substances which more or less behave like ideal gasses, under the additional assumption that the enthalpy of vaporization remains constant in the temperature trajectory. Consequently, students are surprised when the measured boiling point deviates considerably from the calculated boiling point.

Yield against purity

Distillation of crude synthesis mixtures is often carried too far. To the students, changes in smell or colour do not indicate the formation of low boiling or polymeric decomposition and condensation products. Students seem to be rather more interested in yield than in purity and keep on distilling till the last drop.

Physical versus chemical change

Students regard distillation as a physical technique. They tend to ignore possible chemical reactions during the distillation process. For example, there may be a shift in chemical equilibrium due to the changing concentrations during distillation. The crude reaction mixture of some esterification reactions, for example, should therefore be washed and dried before distillation in order to prevent hydrolysis.

The relation between heat capacity of the vapor and the size of the apparatus

The heat exchange between vapor and apparatus and between apparatus and surroundings is often completely disregarded. Especially in a vacuum distillation the heat capacity of the vapor may not be enough to heat the glass ware above the boiling point. As a result, the vapor does not reach the top. In microscale distillations the vapor sometimes cannot reach the condenser because of the heat capacity of the mercury reservoir of the thermometer. We have noticed students watching such processes for a long time without any intervention. And when they interfere, for example by insulating the column, they do not consider the effects on the efficiency of the fractionating process.

Use of boiling point diagrams in distillation

After the lecture course on phase theory some students want to use boiling point diagrams to estimate the possibilities of purifying a synthesis mixture through distillation. They are amazed that there is no table ready at hand with all diagrams for all kinds of mixtures. If they come upon a boiling point diagrams they are often unable to translate the information towards decisions concerning distillation. They do not understand why mole fractions are used as a unit in such diagrams instead of weight or volume percentages.

The amount of water after a steam distillation

Students underestimate the amount of water which will be collected after steam distillation. When the prescription says "the distillate will contain 5 grams of organic product", we have seen students preparing to collect this in a flask of the same magnitude. Sometimes students felt cheated when they found out that, after carrying out a steam distillation, they still had to separate the water from the organic layer.

Problems of teaching assistants
In addition, we should mention that, although we focused on the problems of the students, we noticed that teaching assistants (usually with a Bachelors or a Masters in Chemistry) often had analogous problems. This implies that, if the students are to learn better, teacher training should be part of the solution. Another, more disturbing, conclusion that can be drawn is that the problems apparently are not resolved later on in the curriculum.

Analysis and interpretation from a chemical point of view
From a chemical point of view, many problems fall into either of two categories of problems. The first category comprises the problems due to insufficient understanding of the phenomena and concepts related to boiling, evaporation, vapor pressure, and heat. Of course, without sufficient understanding of these concepts, understanding of the theoretical framework will be immature. This shows in the second category, which comprises problems students have with employing thermodynamics and phase theory, such as the problems with azeotropic mixtures and with the Clausius-Clapeyron equation.
Students do not base their distillation decisions on knowledge of the parameters identity, boiling point, volatility, and quantity of both the mixture and the components. Measurements of pressure and temperature are not used to control the separation process. Decisions and interpretations are not backed up by an understanding of phase theory. Students stick to the independent-substance conception: they regard distillation as a technique to separate liquid mixtures which is based on differences between the boiling points of the components only.

From this initial analysis, an obvious solution to the problems is apparent. From a chemical point of view the problems now have become clear, so we should provide the students with more and better explanations. However, this does not seem to work. We have observed teaching assistants giving excellent explanations both before and during the experiment. Students show every sign of understanding during such talks, they nod their heads, they take notes, but they somehow fail to apply the knowledge in the laboratory. Extra explanations on the spot, for instance when a problem has occurred, seem to work better. In such situations, the student has had an experience, attention is drawn, and specific questions can be asked. We have observed that such an explanation on the spot often leads to improved understanding and performance, presumably because both student and teaching assistant point at the same entities and realize that the other observes and understands phenomena differently. In this situation, questions and explanations are more detailed and specific than is possible during a lecture. However, such discussions only occur *ad hoc*, for example when something goes wrong. Students who do not run into problems do not profit much from this strategy. And, we are afraid that many teaching assistants - who have had the same educational background - never came to understand the details of distillation themselves. They only learned to master the technical manipulations and cannot interpret and discuss problems which do not originate in faults with building the apparatus. Our observations show that teaching assistants often have the same difficulties as students. As a result, both the student and the teaching assistant often try to avoid talking about problems as much as they can.
However, we were unable to place all the problems into this frame of reference. For example, students seemed to ignore the fact that a mixture can have completely different chemical properties than the sum of the independent components. This is especially a problem in organic synthesis, but it is not the same as the problems with thermodynamics or with concepts like vapor pressure as such. The problems that are typical of organic synthesis made us aware that distillations occur in different contexts. Phenomena which are highly important in one context, such as decomposition in organic synthesis, can be ignored completely in other context, for example when determining the boiling point diagram of an ethanol-water mixture. The context at least partially decides what is important and what is not.
This drew our attention to the contexts of the experiments of the laboratory course, and hence to the educational philosophy behind these experiments. We also noticed that the description given

above puts most of the blame on the students. However, we should not forget that these students are acting in a curriculum which we (as chemistry teachers responsible for the laboratory course) have constructed and in which we are communicating with them. Hence, it seems appropriate to take a more fundamental look at the curriculum and at the processes of mutual communication to find clues for understanding the students' problems.

Analysis and interpretation from a constructivist point of view

Implicitly, the standard curriculum suggests that, if an explanation is correct from a chemical point of view, good students should be able to understand and to apply the knowledge in a practical situation. The practical situation only has the extra demand of manual skill, which will be obtained when the student has had some lab training. So we can say that the traditional curriculum has students learn and reproduce theoretical knowledge through lecture courses and paper and pencil tests, and has them learn the technical skills of building the apparatus and executing distillations through tightly prescribed laboratory experiments.

If these are the goals of education, the standard curriculum succeeds at achieving them. The students in our curriculum are able to cope with the tests and the experiments. However, this transfer of knowledge strategy is at odds with the current insights from constructivist theory. From this point of view, meaningful and viable knowledge cannot be constructed on the basis of transfer of knowledge, however correct, only.

The chemists' theoretical knowledge of distillation is based on a generalization from many particular experiences. These experiences stem from many different situations, which we propose to generalize into a few specific contexts: (1) Organic synthesis provides a context in which distillation is used to purify crude reaction products. (2) In analytical chemistry, distillation can be used to determine boiling points and composition of mixtures. (3) In physical chemistry, distillations can be performed to determine the number of theoretical plates of a distillation column, or to construct a boiling point diagram. (4) In the process of making strong liquors, or gasoline, distillation rather is a preparation technique than a separation technique. The way each distillation is carried out depends heavily on specific goals which are determined from within the context.

The experienced chemist can, if necessary, focus on the common elements of each distillation without getting confused by the differences. He or she can speak in a generalized language, and communicate successfully with colleagues to achieve mutual agreement on the purity of a compound, the taste of whisky, or a boiling point diagram.

In education, students and teacher also try to achieve common understanding. In this case, the teacher hopes that the student will eventually interpret and act in the same way as the chemist would. This goal is achieved through experiences with observing, acting and communicating. For this purpose, laboratory work is in principle appropriate. However, our observations lead us to the conclusion that the communication is often obstructed. In the classical curriculum, the road towards understanding does not proceed from experiences in a realistic context towards constructing generalizations, and, after that, from generalizations to theoretical principles. Instead, textbooks and lecture courses start with the generalized, abstract concepts ('distillation is a technique for purifying liquids'), which tacitly presume many contextual features to be known. Furthermore, textbooks and teachers frequently use examples and concepts from different contexts and implicitly mould them into one. Students, of course, are not acquainted with these tacit components. They tend to take the idealized model too literally and apply it to all sorts of distillation, regardless of context. The details of a real distillation, however, very much depend on whether the context is thermodynamics, illustration of separation techniques, or (in)organic synthesis. Having the manual ability to build *a* distillation apparatus is not enough to guarantee success in each specific situation. Since students' expectations are not yet constrained by the contexts we mentioned, students do not notice important details, nor do they interpret their observations from within the theoretical framework that is appropriate to the context. This hinders the communication between student and teacher, because the teacher implicitly has a specific context in mind. We will illustrate this with a few examples.

Context difference within analytical chemistry
A teacher or textbook might say that distillation is a separation technique which is applied to homogeneous liquid mixtures. This formulation implicitly assumes that heterogeneous mixtures are normally separated with a separatory funnel, because this is much easier. However, students can interpret this statement in the sense that it is impossible to apply distillation to heterogeneous mixtures. This leads to confusion in the case of steam distillation.
Context difference between organic synthesis and physical chemistry
The Clausius-Clapeyron equation is sometimes used in organic synthesis to estimate the boiling point of a reaction product under reduced pressure. However, measurements of pressure and temperature in a distillation apparatus can also be used to show that the situation during distillation is not a state of thermodynamic equilibrium, leading to the conclusion that it is thermodynamically illegitimate to use the Clausius-Clapeyron equation. So the use of this equation depends on the context.
Context difference between organic synthesis and analytical chemistry
Distillation is often presented as a purely physical separation technique, without paying attention to the possibility of chemical reactions taking place. Hence, students focus only on the physical characteristics of the mixture. In many situations, especially in organic synthesis, this conception has undesired and unexpected consequences. In general, the emphasis in textbooks is on distillation as a separation technique. A lot of attention goes to explaining why separation takes place, and how to improve the quality of the separation. From this presentation, students can construct the concept that distillation techniques only differ with respect to quality. Of course, all texts mention the reasons for steam distillation and vacuum distillation, but such isolated statements are easily lost in the large amount of difficult and abstract language students have to cope with.
Context difference between analytical chemistry and physical chemistry
In analytical chemistry, distillation aims at purification. Normal distillations show improved purity when the column has fractionating properties. From this point of view, it seems rational always to apply a fractionating column, even in steam distillation. The irrationality of this choice is only apparent from within physical chemistry.

We conclude that the basic problem is that, in the standard curriculum situation, students construct decontextualized concepts for distillation. This leads to difficulties in real chemical contexts. Differences will occur between student observations and decisions and teacher observations and decisions. To be effective in communication, teachers will have to be aware of these differences and of the many implicit context changes that occur in textbooks, lecture courses, laboratory prescriptions, and in their own explanations.
Such a communication, however, will only lead to lasting learning outcomes when the student is able to construct contextualized concepts. For this, experiences with distillation in a variety of contexts are necessary. These experiences should also be used to develop an understanding of the concepts related to boiling, evaporation, pressure, and heat. On the basis of these experiences, generalizations and theoretical explanations can be build.

New laboratory experiments
The ultimate educational goal at the university level is that students base their decisions on theoretical understanding. We concluded that the traditional curriculum, with its combination of lecture courses and detailed laboratory prescriptions, apparently does not succeed in achieving this goal, because the differences in chemical contexts remain largely implicit. Therefore, we have constructed and studied new educational material on distillation which starts with practical experiences and leads towards theoretical understanding. The awareness of the differences between the chemical contexts should be part of this understanding.
To achieve this goal, it is necessary that students have experiences with mixtures, composition, change of composition, and vapor pressure, and also with measuring, controlling, and

describing. An experiment has been constructed in which students take measurements of temperature and pressure in a variety of devices, among them a distillation apparatus and a so called ebuliometer: an apparatus in which thermodynamic equilibrium between liquid an vapor is approximated. When students compare the data they come to understand that certain deviations from equilibrium are intolerable in a thermodynamic context, but are not so important in a purification context. They can develop their own empirical rules of thumb, understand in which situation these rules can be applied, and grasp the different conventions concerning units.

Since the empirical gathering of data is a time consuming job, a video film has been constructed which shows many relations between boiling point and composition at various places and moments in various distillations. This video is presently used in organic synthesis experiments. A new organic synthesis experiment has been devised, in which students have to purify a crude reaction mixture of an esterification without prescription. Many choose to distil, and experience a number of the problems which we listed earlier in this study. This time, the teacher is prepared for these difficulties, and an adequate group discussion can be organized in which the empirical data, such as the top temperature and the quality of the separation are related to the apparatus used, the properties of the components and the mixture, and the preconceptions of the students. The conclusions and generic statements from the discussions are reinforced and expanded by the video, which also links theoretical explanations to the phenomena the students have experienced. The lecture courses in which distillation is explained can now build on experiences, so as to prevent the development of decontextualized knowledge. In this way, we have made teaching distillation more in line with learning distillation.

It would be tempting to compare student performance in the two situations directly and quantitatively. This, however, would do injustice to one or the other approach, since the goals of the two approaches are different. Qualitative observation nevertheless indicates that students perform better and with more understanding in the new experiments.

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